PART 4

New Technology

Feasibility of Advanced Vehicle Control Systems for Transit Buses

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In the course of developing automated vehicle-roadway systems, opportunities to deploy vehicle control systems at intermediate stages of development may emerge. Some of these systems may provide a significant efficiency or safety enhancement to existing operations with manually driven vehicles. Under certain circumstances, transit buses provide an ideal test bed for such systems. A feasibility study for the application of advanced vehicle control systems (AVCS) to transit bus operations is described. Past and present research relevant to automatic control for buses is explored, and specific operations that could be better performed by AVCS-assisted or controlled vehicles are recommended. A survey of feasible technologies for guidance and control of buses is also presented for different levels of automation. During the course of the study, interviews were conducted with several transit system managers in the United States to determine the level of AVCS awareness and interest within the transit community. The findings from these interviews are summarized.

Several nationwide initiatives are currently under way to increase the efficiency of surface transportation. Two of the most important goals stemming from these initiatives are to increase the capacity of the existing transportation infrastructure and reduce energy consumption associated with driving. The idea that we can “build our way out of congestion” has long been rejected, and strategies to increase highway efficiency have been evolving for more than 20 years. Within the national intelligent transportation systems (ITS) program, among those areas that attempt to address these problems are the advanced vehicle control systems (AVCS) and advanced public transportation systems (APTS) user services. AVCS has already contributed to improved safety and efficiency of driving; however, its future effects may be far more significant as enabling technologies develop into fully automated vehicles and roadways with dramatically higher capacity. Like AVCS, applications of technology to public transportation may also significantly improve the service quality and operating costs of transit modes and thus attract more travelers away from automobiles. Rather than let these research areas develop independently it is desirable to study ways that AVCS and APTS can evolve together. The increased operating efficiency and safety that AVCS promises could have a particularly high payoff for transit buses. In this report, the technical and economic feasibility of applying AVCS to transit buses is investigated.

The purpose of this study is to identify bus operations that could benefit from application of automatic guidance methods. An assessment of typical bus system operations as well as the state-of-the-art in navigation and control systems is required. The output is a recommendation for integration of existing needs with available technologies. To arrive at recommendations, a three-step approach was used:

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1. Examine the history of vehicle control and automation associated with transit vehicles,
2. Assess user needs for operational improvements, and
3. Assess available AVCS technologies to achieve improvements.

For a complete picture of the opportunities and technologies available, transit operators, vehicle manufacturers, consultants, and various researchers were contacted. An expert from the public transportation field provided personal insight and access to management at transit properties around the country. From meetings and discussions with this varied group, concepts emerged for incremental deployment opportunities as well as a better understanding of the capabilities and contributions that each could provide toward a system deployment.

BRIEF HISTORY OF AVCS IN TRANSIT BUSES

Although vehicle control has been extensively developed for rail/guideway-based vehicles like trains and automated people movers, relatively little automation technology has been applied to buses. Likewise, despite underlying similarities among buses, automobiles, and trucks, the significant work performed in vehicle control for passenger cars (and, to a lesser degree, trucks) has largely gone untested for buses. On the one hand, this is surprising given the sensitivity of transit operators to incremental improvements in operating efficiency—improvements that appear to be achievable through application of AVCS. On the other hand, because transit is so heavily subsidized there is typically little funding available for development of new technology; available funds are more likely spent on low-risk systems that indicate a more obvious or immediate return on investment. In addition to concerns about cost-effectiveness of AVCS, there are many legal and institutional questions surrounding AVCS and vehicle automation—for example, liability issues in case of accidents as well as passenger and driver fears associated with replacement of drivers by computers.

There is, however, a small body of work in transit bus guidance that demonstrates some of the potential benefits to be derived from AVCS. During the 1920s, and again in the 1960s and early 1970s, various attempts were made to provide guided bus systems. Early studies investigated railbuses that could run on existing railways and take advantage of existing infrastructure and excess capacity. More recently, electronically guided buses were studied for use on roadways. The Barrett Corporation, General Motors, and others investigated and demonstrated bus guidance systems in the 1960s and 1970s but did not place vehicles into service. Since that time, several European bus manufacturers have tested or deployed lateral and longitudinal control systems for buses. Most notably, Daimler-

Benz, Volvo, and M.A.N. developed buses that provided semi-autonomous bus service for extended periods, some of which are still operating. The M.A.N. and Daimler-Benz buses ran under automatic lateral control on dedicated bus rights-of-way (O-Bahn transit system); the Volvo bus demonstration ran under lateral and longitudinal control in the immediate vicinity of bus stops.

The most significant work in bus guidance has been demonstrated by the O-Bahn system, deployed in Adelaide (Australia), Essen (Germany), and elsewhere. The system provides automatic lateral control on express segments of the bus route and conventional (manual) vehicle control elsewhere. Special bus and roadway modifications are required for automatic operations. Both mechanically and electronically guided systems have been deployed since the late 1970s; however, the mechanically guided systems are much more commonly found in service. The mechanical system is guided by horizontal rollers connected to the steering linkage and projected from the sides of the bus bearing against tall curbs. The electronically guided bus follows a current-carrying wire in the pavement by an inductive guidance principle. The magnetic field induced by the current provides a path for the bus, which the bus follows by detecting its lateral position above the wire and actuating the steering rack to center itself in the lane. Similar in principle to conventional bus operations on exclusive bus lanes, the O-Bahn buses run on uncongested bus-only rights-of-way (busways) when under automatic control and on the conventional street network when under manual control, providing benefits of rapid transit performance on line-haul segments and flexible collection/distribution service elsewhere. Furthermore, because the guided buses deviate only slightly from the busway lane, only a very narrow right-of-way is required. This allows for lower infrastructure costs and the ability to construct busways where very little space is available (particularly valuable for bridge and tunnel applications). As a result, O-Bahn systems may be viewed as a favorable alternative to light rail in some transit corridors. The ability to run in narrow rights-of-way may also allow guided buses to share subway rights-of-way with trains. This capability was demonstrated in Essen and allowed improved bus service in the downtown area by taking the buses off the congested surface streets and running them in underutilized rail tunnels.

In parallel with the work in guided buses has been development of automated guideway transit (AGT) systems. Although these systems have been demonstrated with a wide range of vehicle and guideway designs significantly different than those used for bus systems, AGTs set a precedent for unmanned, fully autonomous transit vehicle control. Some notable examples of such systems have been deployed at airports (Denver, Orlando, etc.) and for city transit [Detroit, Miami, Lille (France), London, etc.]. It is worth noting that the automated SkyTrain in Vancouver has among the lowest operating costs of any light rail or metro system in North America with the cost reduction largely attributed to labor savings because of automation (*1*). Personal rapid transit (PRT) concepts involving the use of small automated guideway-based vehicles serving a dense network of origins and destinations have been investigated for at least 30 years, but in the past few years there has been renewed interest in these concepts as traffic congestion has worsened and technology has improved. Raytheon Electronic Systems of Marlborough, Massachusetts, is currently building a small PRT system for Northeastern Illinois Regional Transportation Authority (RTA) in Rosemont, Illinois, and feasibility studies of other systems are under way around the world.

BENEFITS OF AVCS FOR TRANSIT BUSES

It is clear that the value of public transportation is based on the achievement of many different, and often conflicting, goals. To avoid confusion, the viewpoint(s) of transit operators and users (and potential users) are assumed in this paper. From this perspective one can say that any system that reduces capital and operating costs or improves transit service quality (where service quality is loosely defined by such parameters as travel time, fare, safety, comfort, convenience, etc.) is considered an improvement.

In assessing the benefits of AVCS for transit buses, a review of existing transit bus operations was performed. From literature reviews, system tours, and interviews with transit experts, several operational areas emerged as suitable for AVCS improvement:

- Lane keeping,
- Platooning,
- Curbside docking,
- Terminal operations,
- Maintenance operations, and
- Collision avoidance.

Each of these operational areas and the associated AVCS benefits are discussed in the sections that follow.

Lane Keeping

Performance of the lane-keeping task, common to all roadway vehicle operations, is more critical for wide vehicles like buses and trucks than for automobiles, because lateral distances to the lane edges are reduced. Lane-keeping systems have been prototyped to provide various degrees of lane-centering control ranging from driver warnings to full steering control. The value of a lane-keeping system exists for all road-going vehicles, particularly as an aid to driver inattention where lane changing is infrequent (such as freeway driving). However, there exist specific operations for transit buses that could be substantially improved with the aid of a lane-keeping system. One example is operations in tunnels or other narrow segments of the bus right-of-way. A number of bus systems in the United States incorporate bus operations in one or more tunnels. Operations on these narrow segments require the drivers to trade off operating speed for safety. A fatal January 1996 collision between two buses in Pittsburgh was caused by one bus that crossed out of its lane and into the lane of an approaching bus. After this accident the system operator was required to reduce the speed of operations on this route, thus creating a longer schedule and reduced quality of service. This could be a case where a lane-keeping system would provide a better level of safety and allow higher speed operations.

Other benefits of a lane-keeping system could accrue as the transit system infrastructure adapted to take full advantage of the lateral control capabilities of buses. For example, as demonstrated in Essen, Germany, there may be significant benefits associated with running buses along with trains in subway tunnels. Significant bus service improvements could be realized in cities by moving buses from congested surface streets to underutilized subway tracks. A lane-keeping system would be a critical enabling technology for such a transition. Likewise, land acquisition and construction costs would be reduced where guided busways or segments are built as a result of reduced lane-width requirements.

This advantage for laterally guided buses would be most significant where it is necessary to add or reallocate bridge or tunnel rights-of-way. As an example, London Transport is considering construction of two narrow guided bus lanes in addition to four conventional traffic lanes for a new bridge to the Docklands area. The agency perceives that the modest increase in bridge width required for guided bus lanes would provide substantially more traveler-carrying capacity than other alternatives. Finally, a lane-keeping system could provide an early deployment opportunity for automated highway systems as a system building block. A lane-keeping system would pave the way to more sophisticated vehicle control systems and provide immediate benefits for existing transit bus operations.

Longitudinal Control

Operations that would benefit from application of longitudinal control may take one of two forms: general automatic speed control or the special case of platooning. General automatic speed control would be used to precisely maintain desired headways between buses for headways up to 1 or 2 min long. This type of control would be reserved for high-frequency operations where slight variations in headway would disrupt operations. Platooning represents the high-frequency operational limit of speed control where headways approach several seconds or less. The efficiency advantages of platooning vehicles are clearly demonstrated by the superior productivity of trains relative to buses on high passenger demand routes.

In the case of high-volume transit service, there are very few North American bus operations that carry sufficient passenger volume to justify platooning to increase capacity. Perhaps the only operation of this scale in the United States runs on the Lincoln Tunnel exclusive bus lane that connects northern New Jersey and Manhattan and carries over 700 buses per hour during the peak hour (*2*). If capacity constraints within the bus terminal can be resolved, there is the potential to expand the capacity of this lane further by applying longitudinal control systems that can safely maintain very short headways between buses without mechanical couplings and keep the bus flow very steady. In the long term, a successful demonstration of platooning on an express lane might motivate transit planners to consider dedicated guided busways with bus platoons as an alternative to light rail in more heavily traveled corridors. To significantly reduce labor costs, this system could conceivably be demonstrated to run trains of buses under lateral and longitudinal control with a single lead driver (or perhaps no driver). Such a system could approach the operating efficiency of trains on moderately high volume routes and use much cheaper vehicles with the flexibility to be run on conventional roads (Figure 1). Autonomous vehicle-following technology has been successfully demonstrated for several years by various research institutes and vehicle manufacturers.

Although the Lincoln Tunnel case would provide an opportunity to demonstrate longitudinal control to improve the capacity of an express segment of a bus route, much shorter platoons could also provide capacity benefits for nonexpress operations. The concept of a "virtual artic" (two or three platooned buses that move as a single bus with the passenger-carrying capacity of a single or double articulated bus) comes to mind. On some routes or route segments it may be advantageous to use the operational efficiency of large-capacity vehicles, even if each vehicle still retains a driver onboard. An example of a transit system where this approach might be feasible is Seattle (King County Metro). If Seattle determines that it needs to significantly increase bus volume through its downtown bus tunnel, it may need to use platooning methods to achieve this increase. The use of platoons in the tunnel would allow dwell time at stops to be shared simultaneously by several buses and thus would provide for a significantly higher bus capacity than could otherwise be offered. A longitudinal control system could safely facilitate the formation and maintenance of these platoons in the tunnel.

Short of automatic platooning, a speed-control system to precisely maintain short headways of approximately 1 min or less would be advantageous on some high-volume transit lines. This approach could help to reduce the problem of bus bunching that often occurs on such routes when one bus slips from its schedule and following buses close the gap from behind. Within bus terminals longitudinal control could also be used to ensure sufficient slot size (traffic gaps) to allow safe merging of accelerating buses from ramps or platforms. Chicago Transit Authority is interested in maintaining steady speeds and short headways on approaches to major bus stations where multiple lines share a single platform. By carefully maintaining headways on the approach to the station, each bus

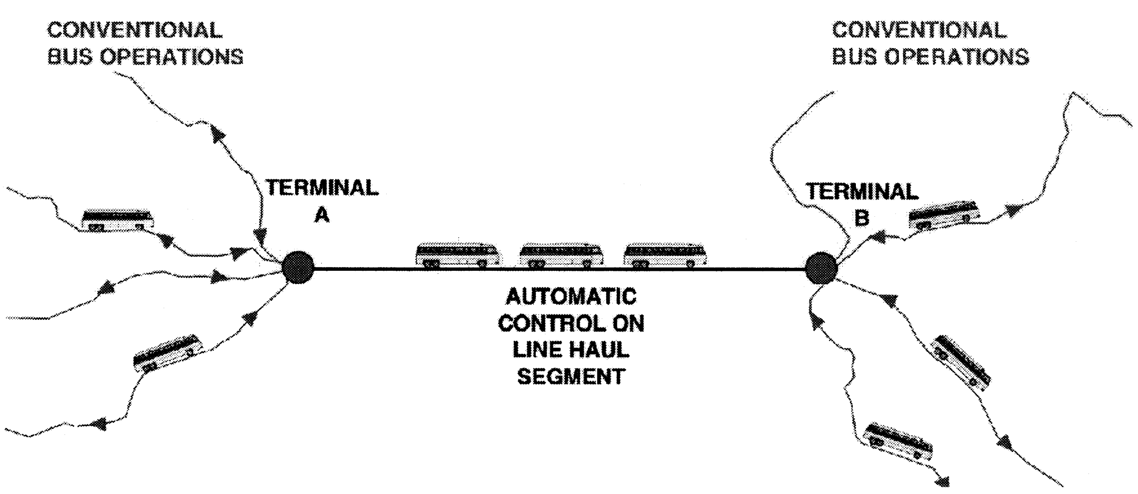

FIGURE 1 AVCS concept for bus operations.

will arrive separately, thus minimizing passenger confusion. One possible limitation for automatic speed control applications may arise when buses drive in mixed traffic, as the desired vehicle speed may not be possible under existing traffic conditions.

Curbside Docking

The presence of a gap or height differential between bus doors and the curb or platform area causes inefficient and inconvenient operations at bus stops. The provision of a level loading surface without gaps allows for much easier passenger access and egress and minimizes dwell time at stops. Another significant advantage for level loading is improved access for the physically disabled. Level-loading buses also eliminate the need for wheelchair lifts, which are expensive, maintenance intensive, and time-consuming to operate. To capture the advantages of level loading, however, there must be little or no gap between the bus and the curb and thus automatic control of the bus for precise placement is desirable to ensure consistent and efficient docking. The curbside docking concept was successfully demonstrated in Sweden by Volvo in the late 1970s but was later removed because drivers did not believe that it was necessary (*3*). This system, which used an inductive wire guidance principle, is also noteworthy because it incorporated both steering and braking control on the approach to a bus stop. More recently, Renault has been experimenting with a machine vision-guided bus prototype for accurate curbside docking. Apparently there are plans to deploy a small fleet of low-floor Renault buses with this automatic docking system in the city of Grenoble.

Terminal Operations

There exists a wide diversity of bus terminals, from the very complex like Port Authority in New York, to the simple suburban bus depot. Within terminals there is generally a significant amount of starting, stopping, turning, and perhaps backing within a confined area in terminals. In higher-volume facilities there may be frequent conflicts, wrong turns, and occasional accidents, all of which contribute to reduced safety and operating efficiency. AVCS may have some applications in terminals, particularly congested ones where drivers must quickly determine where to go or risk causing a bottleneck (or worse). Some concepts that may have future use in terminals are automatic sorting of incoming buses into berths and outgoing buses to access lanes, assisted or controlled backing operations, merge control via longitudinal control system, and collision-avoidance systems. If high-volume busways and bus lanes become more popular in the future, automation of terminal operations will become more critical at the entrance and exit points to the facilities. Ultimately, if all buses are assumed to run under automatic control in the terminal areas, the terminals can be smaller and with less lateral clearance and shorter entrance and exit lanes.

Maintenance Operations

From discussions with several transit system operators, it is clear that any incremental reductions in operating expenses would be embraced. A significant number of operators interviewed believe that bus service and maintenance operations could be streamlined with application of AVCS. Every day routine operations are repeated by dedicated maintenance staff who drive buses between stations to perform various tasks. For example, at Port Authority Transit (PAT) in Pittsburgh there may be one to five drivers at each of several garages across the city. At the end of each bus's service period, the driver takes the bus through a fueling area, a fluid check area, and a washing area and then parks the bus in a designated space (Figure 2). By automating the movement of buses through these

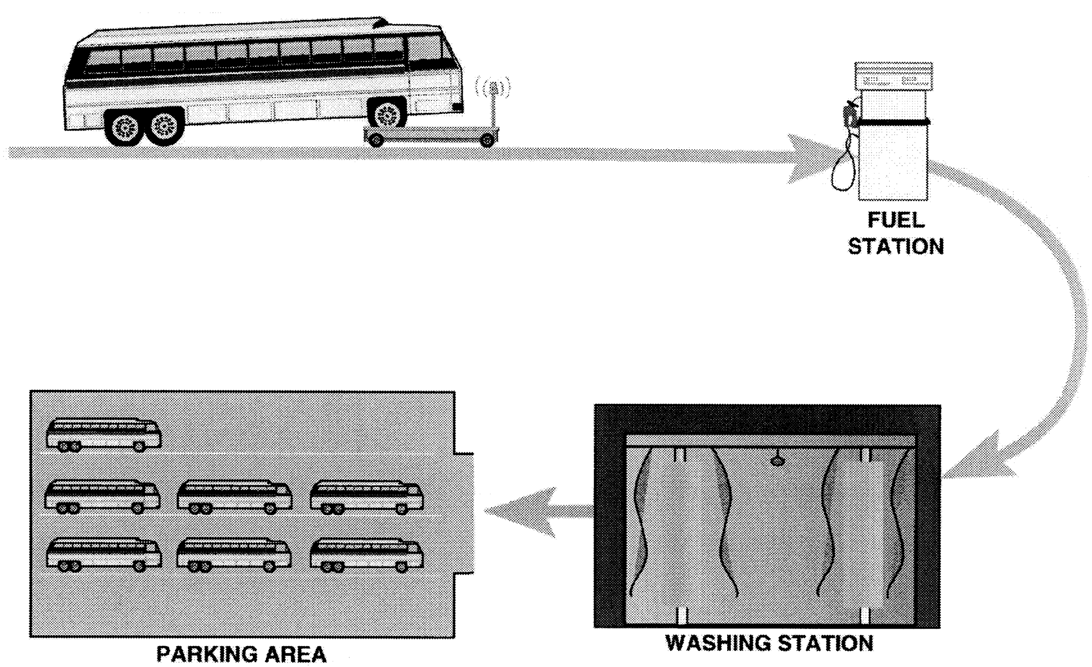

FIGURE 2 Concept for automatic movement of buses in maintenance garages.

areas, PAT could reduce operating expenses. Instead of using several drivers at each facility, there could be one or two dedicated service technicians to perform the necessary maintenance operations while the bus moves autonomously through the facility. Heavy-duty automated guided vehicles (AGVs) currently exist for the precise and automatic movement of 50-ton (45 372 kg) containers within large port areas. A dedicated AGV could be installed at each service facility to pull buses between stations. The relatively controlled environment of the maintenance area combined with the immediate benefits provided by AVCS make this a strong candidate for a system deployment.

Collision Avoidance

Like lane keeping, collision avoidance is under investigation for all types of vehicles. Several transit operators interviewed expressed interest in cost-effective collision-avoidance systems, particularly rear-end collision-avoidance systems. NHTSA and various automotive manufacturers and suppliers are actively working toward collision-avoidance systems to reduce the frequency and severity of a wide assortment of collision types. Delco Electronics currently markets a near-obstacle detection system for school buses by using radar transmitters mounted below the bus to warn of obstacles outside the driver's field of view; until very recently Greyhound's intercity bus fleet was equipped with Eaton VORAD's forward-looking radar systems for collision avoidance. If these systems proliferate and prove their value, transit buses may gradually become equipped as well.

ATTITUDES OF TRANSIT COMMUNITY TOWARD AVCS

In the course of this research effort many transit and AVCS studies were analyzed and a wide variety of transit industry experts were interviewed, including transit system operators, transit planners, bus manufacturers, transit consultants, and researchers. The question underlying this examination was What tangible benefits can AVCS provide for public transportation systems? In particular the focus was to determine feasible and near-term AVCS opportunities for transit buses. During the study it became readily apparent that there was very little appreciation within the transit community for the benefits that AVCS could provide.

Once the AVCS concept was thoroughly explained, the overall consensus of the transit community was that AVCS showed exciting potential for the distant future but much less promise for the immediate future. The more visionary planners imagined dramatic service and operating cost improvements, with guided buses running on busways and subway tracks and automated buses moving assembly-line style through maintenance garages; less optimistic planners did not believe that AVCS could provide many significant benefits even if the technological and institutional hurdles could be overcome. New technology comes slowly to the transit world, and vehicle control systems are perceived to be several steps beyond the current cutting-edge systems, which are typically information flow oriented, like real-time fleet management and traveler information systems. Transit managers cannot afford to be adventurous from either a cost or an operations standpoint because there is little or no funding available for experimentation and a system failure is unacceptable to the riders who rely on the service. A transit consultant in Ft. Lauderdale, Florida, who unsuccessfully lobbied for deployment of a guided busway (O-Bahn type) to connect the airport and ship port area found decision makers were unreceptive to the new technology; their attitude was that other properties would already have deployed such systems if they were cost-effective and reliable. Another planner from a forward-thinking agency said of new technology initiatives: "I like to be the second guy to adopt new technology, but not the first." Reflecting the fear of system failure, one transit system manager indicated that he would seriously consider vehicle automation technologies if it could be proven to him to be "100 percent reliable"—an unrealistic goal for any system.

In Pittsburgh, PAT planners expressed a willingness to invest capital funds in new technologies that could reduce their operating costs but were concerned that AVCS approaches might spark fear of job cuts among workers and lead to poor labor relations. Most planners also expressed concern that completely unmanned buses would be difficult because of fare collection and passenger security; however, it was accepted that these concerns might be addressed, at least in the short term, by providing lower-paid bus attendants on automated buses. Although many transit systems demonstrated opportunities for short- and long-term AVCS deployment, it is the long-term deployments (with facilities and vehicles designed to accommodate AVCS) that offer the highest payoffs. Unfortunately the enabling technologies for the future must evolve from short-term applications, like lane keeping and other systems, which may not provide such a high cost-benefit advantage. Even the most protechnology transit property requires a compelling economic analysis of the costs and benefits of an unproven technology approach like AVCS.

From the industry side there was also cautious interest in AVCS. A transit industry consultant with expertise in the design and deployment of AGTs pointed out that with labor typically representing 75 percent of operating costs, any incremental labor cost reduction that AVCS could provide should be considered seriously. He also indicated that it would be important to get the bus manufacturing industry interested in AVCS, as they would need to contribute to the design and production of an AVCS-equipped bus. This may be a challenge because the level of research and development funding is typically very low in the bus industry and manufacturers need to see a strong demand from their customers to justify any exploration of AVCS. An engineering representative from the North American bus industry echoed this sentiment, saying that his company is customer driven and does not have the resources or desire to develop new systems. Several European bus manufacturers, however, have proven their interest in vehicle-control technology by deploying guided buses and investing in guidance technology.

AVCS TECHNOLOGIES FOR TRANSIT BUS APPLICATIONS

In this section an exhaustive or thorough description of all navigation and guidance technologies available is not provided, but attempts are made to illustrate the most promising technologies for a near-term system deployment. Although several distinct systems are described here as alternatives, it is quite likely that the ideal AVCS for a given task will incorporate more than one of these technologies simultaneously.

Wire Guidance

As described previously, the inductive guidance system demonstrated on O-Bahn buses has a long history in vehicle control. The guidance system has been used for years by AGVs on factory floors and in other areas. Among its technical advantages wire guidance is robust, proven, and relatively simple. Among its disadvantages, wire guidance is infrastructure intensive and inherently inflexible, as it requires the presence of a wire path to any location that a vehicle needs to reach.

Differential Global Positioning System

The global positioning system (GPS) has been used for several years in tracking vehicles, seacraft, aircraft, and so forth. The system, which incorporates line-of-sight communications between orbiting satellites and a receiver anywhere on earth, provides positional accuracy on the order of 100 m for general users. To greatly improve accuracy, signal processing enhancements, collectively called differential GPS (DGPS), have been introduced to correct signal transmission degradation between the satellites and a receiver. Research in recent years has shown that DGPS can provide positional accuracy in the 5-cm range—sufficient to make this technology viable as a navigation system. Although there are disadvantages associated with GPS, its major inherent advantages are high accuracy and available existing infrastructure (satellites and ground stations). Many in the AVCS community believe that in the future DGPS will provide one of the basic guidance technologies for vehicles.

Machine Vision

Image-processing techniques have been under development for many years and have been successfully implemented in automobiles and other mobile robots for guidance. Among advantages, machine vision systems require little or no infrastructure modifications, have been shown to provide excellent positional data for vehicle guidance, and may be configured to perform many different tasks (from lane keeping to collision avoidance to road sign reading, etc.). Some disadvantages are current system expense, complexity, and inherent limitations of the basic sensor (camera), which can provide information only on the scene immediately visible to it.

Passive Magnetic Trails

Like the guided-wire system, the underlying guidance principle of magnetic trails is to provide a path in the pavement for a vehicle to easily follow. Unlike guided wires, however, passive magnetic trails do not require electricity. Two approaches are currently under investigation: discrete magnetic markers and a continuous magnetic stripe. The California Partners for Advanced Transit and Highways program based at the University of California, Berkeley, has investigated the discrete markers method and has successfully demonstrated its capability for lane keeping. Magnetic road tape research is under way in Minnesota with an effort by 3M to incorporate ferrous material into a conventional pavement marking tape. Like wire-guided systems, magnetic trails may provide reliable and accurate lane keeping, but they are infrastructure intensive and relatively inflexible.

OPPORTUNITIES IN SPECIFIC TRANSIT SYSTEMS

Pittsburgh

PAT's system is one of the more suitable for AVCS deployment because it could benefit from AVCS in both the near and the long term. In particular, PAT operates the only dedicated and grade-separated busways in the country (Figure 3), providing an excellent testbed for vehicle control testing and development. On the basis of conversations with PAT staff it appears that they are generally receptive to new technologies that can legitimately reduce operating costs or improve service quality. They expressed willingness to contribute at least some capital funding to the deployment of AVCS if such a system could be justified. Given the controlled nature of the busways relative to conventional roads as well as the fact that PAT owns and operates both the busways and the buses, Pittsburgh may be an ideal location for AVCS deployment.

The PAT system includes two dedicated busways (east and south busways) built on existing rail rights-of-way and a third busway (airport busway) currently under construction. Unlike the existing two busways the airport busway will share its right-of-way (at least initially) with high-occupancy vehicles (HOVs). The system also incorporates reserved bus lanes on surface streets in the central business district (CBD) as well as a small subway network in the CBD. Some promising possibilities for near-term AVCS deployment include a lateral control system for lane keeping on the busway as well as automated vehicles for bus maintenance in service garages. In light of a fatal accident on the east busway in early 1996 in which a bus crossed into the approaching lane and hit another bus head-on, there is genuine interest in any system that could supplement the driver in the lane-keeping function. With respect to the maintenance garage automation, there may be an opportunity to deploy an AGV to push and pull buses through the

FIGURE 3 PAT bus on Pittsburgh's east busway.

garage during servicing. In the longer term lateral and longitudinal control could be applied to allow buses to run in the subway with trains. This vision of PAT's former executive director, Bill Millar, would improve trip times significantly and eliminate the need for downtown transfers in some cases. Another possibility for automation exists on the east busway between downtown and the Wilkensburg terminal 6 mi (9.66 km) away, where the busway ends. Buses could be run autonomously or in platoons (with or without a leading bus driver) between these points and drivers could board the buses at either end to service routes from there. This would allow continued service levels with fewer drivers because of automation of the line-haul portion of the trip.

Cleveland

The Cleveland RTA staff were interested in AVCS and new transit technology in general. Deputy General Manager Ron Barnes was particularly interested in the potential of AVCS for RTA's operations. His opinion was that AVL and traveler information are the new technologies of the next few years, but RTA must consider revolutionary technologies such as AVCS now to effectively plan for the 5-, 10-, and 20-year time horizons. Of particular interest was the maintenance area automated vehicle concept described above. There are several major garage renovations planned in the coming years and Ron believed that AVCS should be considered in these plans.

Interest was also expressed by RTA planners for the Euclid Avenue corridor, which will undergo a major bus transit service improvement in the next several years. An option that may be considered for the corridor is a guided busway. Given the limited available road width, and the guided busway's narrow right-of-way requirement, this approach might suit RTA's needs.

Seattle

King County Metro of Seattle has long been recognized by the transit community as one of the most innovative and forward-thinking agencies in the United States. The overall transportation system, particularly the transit system, reflects a real commitment to intermodalism, high-quality transit service and a consideration of all system users. The county is willing to apply unconventional transportation solutions as witnessed by its public horse trails, bike racks on buses, free electric bus service through its 1.3-mi (2.1-km) bus-only subway, and other services. In addition to the bus tunnel and subway Seattle also has a several-mile-long dedicated busway segment. Paul Toliver, the director of King County Department of Transportation, is a strong proponent of new technology and he and his staff were interested in AVCS. The automated servicing application was very interesting to them, and they indicated that such a system would be considered for a new garage design currently under study.

Other opportunities for AVCS might exist for lateral bus guidance (lane keeping) or platooning for the buses as they travel through the tunnel. Platooning may be the more significant capability in the future, as there is a possibility that tunnel volumes will increase. In particular, if light rail vehicles are introduced to the tunnel it will become more critical that buses use their time in the tunnel more efficiently or else risk causing delay to other buses and trains on short headways. The use of low-floor buses in platoons should provide that level of efficiency in the future. As with Pittsburgh, these platoons could be completely automated or semi-automated (with a driver in the lead bus only) to provide significant operational labor-cost reductions within the tunnel. Given the dedicated infrastructure and downtown free-ride policy (no fare collection issues), the bus tunnel might provide an ideal point of deployment for fully autonomous buses. Drivers could enter and exit buses at the two ends of the tunnel for local service routes and the line-haul tunnel segment in between would be automated.

Houston

More than any transit agency in the country, Houston METRO has embraced AVCS approaches for their bus operations. With a network of more than 100 mi (161 km) of HOV/busway throughout the metropolitan area, Houston's management, led by General Manager Bob MacLennan, has visions of lane-keeping and platooning operations on these facilities in the future. The agency has invested in excess of $1 million to fund research and development initiatives in the AVCS arena (unique among properties in the United States), primarily for the automated highway system demonstration scheduled for August 1997. In preparation for this technology demonstration, Houston has worked with AVCS developers to design and install a machine vision-based lane-keeping system and a radar-based longitudinal control system for two low-floor New Flyer buses that will drive autonomously along an I-15 HOV lane outside of San Diego. METRO has also expressed interest in other applications for vehicle automation, including their bus maintenance operations.

Other Areas

In addition to the specific cities listed above, there are other cities and regions that may be suitable for an AVCS deployment. In the course of this study, it became clear that transit systems in each city have their own unique opportunities for AVCS, whether it be for narrow tunnel segments, dedicated bus lanes, abandoned or shared rail rights-of-way, or other opportunities. New York City, for example, has the famous Port Authority terminal and Lincoln Tunnel express bus lane leading to it from New Jersey. As mentioned previously, this system could benefit from AVCS approaches, particularly automatic platooning on the bus lane and lateral control within the terminal. In Miami, Metro-Dade Transit recently opened several miles of exclusive busway on an abandoned rail right-of-way running south from the city, with plans to open additional segments in the future. A transit planner there expressed interest in AVCS applications to improve service quality. Beyond the basic benefits of AVCS, he thought there might also be some marketing appeal to the public for a high-technology bus.

An interesting development that may encourage the introduction of AVCS is the increasing popularity of busways. Although very few dedicated busways exist in this country today, many transit planners are now considering busways and occasionally guided busways as alternatives in their corridor studies. Boston, Philadelphia, Milwaukee, Raleigh, Silver Spring (Maryland), and Cleveland are only a few of the jurisdictions that are considering or that recently considered busways. These bus-only facilities are the most suitable for adaptation of lateral and longitudinal control systems, as they present a relatively controlled environment for integrating new equipment on buses and the facility itself.

RECOMMENDATIONS FOR FUTURE WORK

From a review of transit industry needs and available AVCS technologies, some recommendations have been identified for continued work in the near term. These recommendations are summarized here:

- Automation of bus movement through service areas in bus garages was the most popular AVCS vision for transit operators. Some managers asked how much a system of this type would cost. This should be a high-priority area of study for future work. Specifically, a detailed study of vehicles, facilities, and servicing operations at an interested transit property should be performed and a small handful of AVCS technology providers contacted to work toward developing alternative design concepts and cost estimates for such a system.
- A design concept and cost estimate for a lateral control system for lane keeping should be developed. As described previously, there are many potential benefits for lane-keeping systems in the near and long term as well as many levels of deployment possible, from warning systems to full lateral control. In cooperation with specific technology providers, transit agencies, and bus manufacturers, alternative system concepts should be developed and a cost estimate established for each alternative.

CONCLUSION

During this study, numerous contacts within the transit industry were interviewed and four major transit operations were toured and reviewed. There were also many meetings within the AVCS community, including briefings to the National AHS Consortium, the ITS America AVCS Committee, and other AVCS experts and providers. Although tremendous opportunity exists for AVCS in transit, successful implementation requires cautious steps. Short-term benefits of AVCS certainly can be demonstrated with modifications to existing vehicles and infrastructure, but to fully capture the larger long-term benefits will require vehicles, infrastructure, AVCS equipment, and many transit agency processes (like route planning, scheduling, and operations) to be coordinated together as a unified system. In the course of this study, two significant observations have emerged:

1. Very little shared knowledge exists between the AVCS and transit community.
2. Like so many other pioneering ITS initiatives, the deployment of AVCS for public transit will encounter more significant institutional and legal hurdles than technical challenges.

The importance of the first point cannot be overstated. Effective system design requires understanding the entire system and the interactions between all the components. From a technical standpoint, an effective large-scale AVCS deployment requires detailed understanding of issues associated with bus operations, vehicles, infrastructure, sensor technology, control system design, and many other issues. The second point indicates the importance of incorporating many nontechnical issues into the design process. There are major financial considerations as well as legal and institutional barriers. There are transit system managers, transit employees, and the riding public who all need to accept the changes that AVCS would bring. From the standpoint of transit management, there are many risks associated with AVCS, not the least of which are angry labor unions and lawsuits in the case of system failure. With so little funding available for new technology at most agencies, there is a high opportunity cost associated with testing relatively unproven technology.

Despite the challenges, however, this study has served to start the transit community thinking about the potential benefits of AVCS. Some of the planners and administrators interviewed indicated that they may now start considering AVCS options in their analyses of alternatives for future projects. A convincing case study of AVCS for transit buses, demonstrating cost and service quality advantages, would certainly provide further momentum to a vehicle control system-based approach.

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